AD-A038 848 ARMY MATERIALS AND MECHANICS RESEARCH CENTER WATERTO--ETC F/G 11/6
WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP.(U)
DEC 76 S V ARNOLD, P J DOYLE

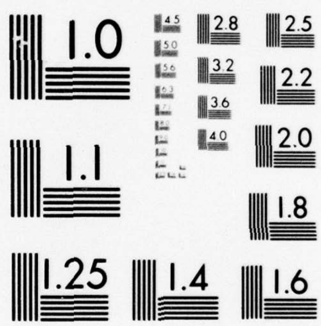
UNCLASSIFIED AMMRC-TR-76-41 NL

| OF |

AD
A038848

END

DATE
FILMED
5-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AMMRC TR 76-41

(12)
NW

AD

WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP

STUART V. ARNOLD and PAUL J. DOYLE
MATERIALS APPLICATION DIVISION

December 1976

Approved for public release; distribution unlimited.

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

DISPOSITION INSTRUCTIONS

Destroy this report when it is no longer needed.
Do not return it to the originator.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 AMMRC-TR-76-41	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP.		5. TYPE OF REPORT & PERIOD COVERED 9 Final Report,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Stuart V. Arnold [redacted] Paul J. Doyle		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Army Materials and Mechanics Research Center Watertown, Massachusetts 02172 DRXMR-K		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: AMCMS Code: 692000.75014 Agency Accession:
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Materiel Development and Readiness Command Alexandria, Virginia 22333		12. REPORT DATE 11 Dec[redacted]76
		13. NUMBER OF PAGES ~~10~~ 12 24p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Titanium alloys
Heat treatment
Mechanical properties
Forming

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE SIDE)

403105

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Block No. 20

ABSTRACT

Continuous strip of Ti-8Mo-8V-2Fe-3Al was investigated for possible application in the nose cap for the main rotor blade of the Heavy Lift Helicopter as part of the Advanced Technology Component Program. Aging response of strip solutionized in a continuous vacuum annealing furnace and subsequently cold rolled was determined as functions of time and temperature for several levels of cold reduction. Tensile and fatigue properties of strip produced by selected practices were measured. Feasibility of creep forming solutionized-and-cold-rolled strip to nose cap contours during aging was explored. Warm die forming and aging of strip to those same contours was demonstrated.

UNCLASSIFIED

CONTENTS

INTRODUCTION

During conduct of the recent Heavy Lift Helicopter Advanced Technology Component Program (HLH-ATC) nose caps for the leading edge of main rotor blades for the developmental aircraft were creep formed from blanks of Ti-6Al-4V alloy strip 40 feet × 32 inches × 0.060 ± 0.003 inch in size. Creep forming was done at 1600 F over a male die in a car-bottom furnace. Interaction with air during the lengthy cycle resulted in alpha-case formation requiring removal of 0.004 inch of contaminated metal from each surface of the blank by chem-etching. Fatigue properties of mill-product strip after forming and chem-etching were less than anticipated and below design requirements. Because the blade was weight-critical, recourse to Ti-6Al-4V strip of heavier gage was not permissible.

Two approaches to resolving the problem were undertaken: (a) modification of Ti-6Al-4V strip rolling practice to produce textured material with directionally higher fatigue strength, and (b) investigation of Ti-8Mo-8V-2Fe-3Al alloy (Ti-8823) strip as a possible alternate. Because technology for the former approach was thought to be more advanced at time of the ATC program, blade development proceeded using the textured (directional) strip. This report describes the second approach which was carried out as a lower priority backup measure using funds provided by the office of the Project Engineer, HLH-ATC, Army Air Mobility Research & Development Laboratory, Ft. Eustis, Virginia. There were three objectives of the subject investigation:

(a) Determine whether cold rolling could be used to accelerate aging response of solution-annealed Ti-8823 strip in a controlled fashion to produce material with mechanical properties suitable for the nose cap application.

(b) Determine whether nose cap radii could be creep formed at aging temperatures.

(c) Determine whether nose cap radii could be die formed at aging temperatures.

The first objective was accomplished in part by TIMET, a division of Titanium Metals Corporation of America under Contract DAAG46-74-C-0030 (see Appendix). AMMRC, using strip produced by TIMET, measured fatigue properties corresponding to selected aging cycles and conducted forming experiments.

TEST PROCEDURE

Fatigue Testing

Solution-treated-and-35%-cold-rolled 0.060-inch strip provided by TIMET was aged at AMMRC according to the following cycles:

Aging Temperature	Aging Time
1110 F	30, 60, 120 minutes
1150 F	30, 60 minutes

The composition of the ingot from which this strip was rolled appears on page 2 of the Contractor's report (see Appendix). Photomicrographs of the strip material are shown in Figure A-1 of the Appendix.

After the aged strip material had been chem-etched to remove 0.001 inch of metal from each surface it was fashioned into longitudinal fatigue specimens of the design shown in Figure 1. This design was intended to reduce edge-initiating fracture and avoid fretting associated with pin-loading. Six specimens for each aging condition were tested to failure or run-out (10^7 cycles) in alternating (15 Hz) tensile stress, R = 0.10, using a 20 kip MTS closed-loop fatigue system.

Creep Forming

A simple fixture was constructed which provided a horizontal pin of 0.25-inch radius over which a length of strip could be balanced with weights attached to each end. This apparatus was placed in an electric furnace and raised to selected temperatures to determine whether creep would bring about conformity with the pin radius within acceptable time/temperature cycles (see Figure 2).

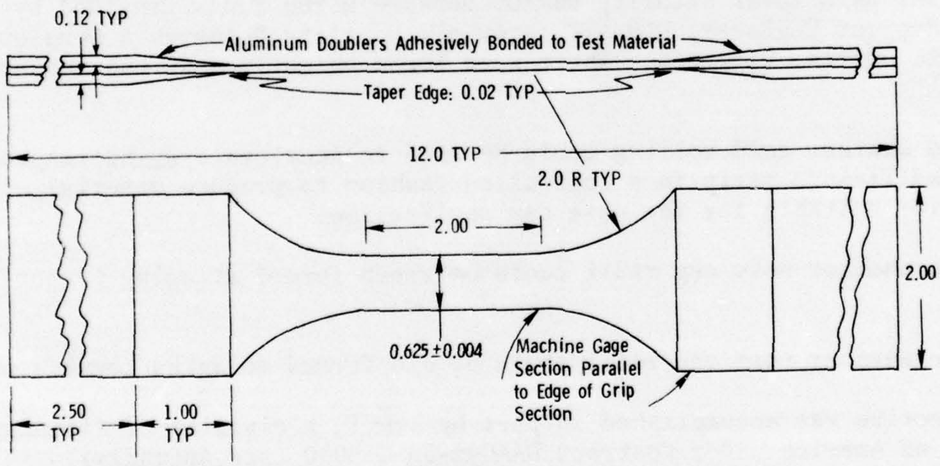


Figure 1. Fatigue test specimen design for sheet materials.

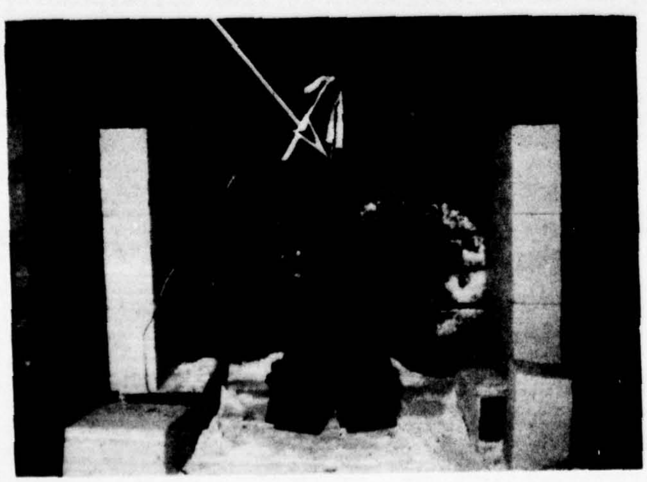


Figure 2. Apparatus for creep forming Ti-8823 strip over 1/2-inch-diameter pin (see arrow).

Die Forming

Several die fixtures, see Figure 3, were constructed to simulate nose cap contours. The nose radii of these dies were 0.25, 0.50, and 0.75 inch, corresponding to the range of radii at various stations along the length of the nose cap. As-received (solution-treated plus 35% cold-rolled) Ti-8823 strip was cold formed in these dies, then removed and checked for spring-back. Strip was also cold formed and retained in the dies, which were placed in a furnace and held for the desired aging cycle. Strip was also warm formed at aging temperature and held in the dies to complete the aging cycle.

DISCUSSION OF RESULTS

Fatigue Tests

The fatigue specimen designed for this program avoided the problem of fretting, as was intended, but did not prevent edge-initiating fractures. Indeed, trial specimens disclosed that fractures were prone to start in the radius just beyond the gage length. This was thought to result from a change in cutting conditions at this point during the numerically controlled milling operation. Increased care in edge preparation alleviated (but did not eliminate) this difficulty in the test series. It may be remarked that for fatigue testing Boeing-Vertol Company (contractor for the HLH-ATC program) uses a rectangular 12 inch × 2 inch strip specimen with doublers cemented on each end. This latter design is much simpler to machine, but it results in a portion of edge-initiating fractures.

The aging treatments for the fatigue test series were selected on the basis of tensile data shown in Table III of the Appendix. Longitudinal properties are shown plotted against aging time in Figure 4. Since aging of solution-treated Ti-8823 strip requires 4 to 8 hours, 35% cold reduction has accelerated response considerably and in a controllable, reproducible fashion. It appears that yield and tensile strenths fall off logarithmically with aging time while ductility increases. It should be noted that the spread between longitudinal and transverse properties of the aged strip is quite moderate. Since no property advantage accrued from the 480-minute cycle, shorter cycles (30, 60, and 120 minutes) were selected for the test series on the premise that these would cut production time and reduce contamination.

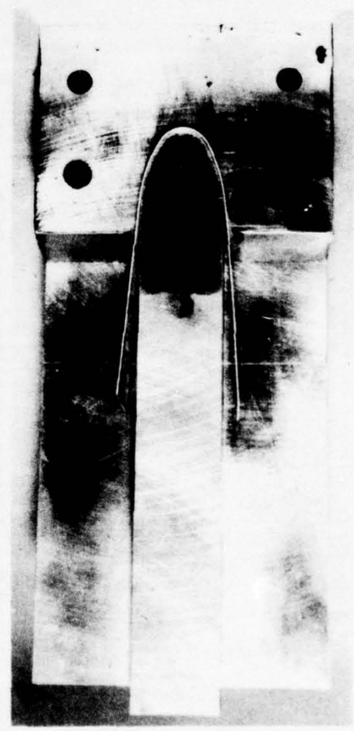


Figure 3. Disassembled die for warm forming Ti-8823 strip to simulated nose cap contour.

19-066-217/AMC-75

Fatigue test data are presented in Table 1 and plotted in Figure 5. Reference to Figure 5a will show that specimens aged 120 minutes at 1100 F were marginally better than those aged 30 minutes at that temperature; those aged 60 minutes were poorer. Run-out at 40 ksi alternating stress may be projected for specimens aged either 30 minutes or 120 minutes at 1100 F. Figure 5b shows that specimens aged 30 minutes at 1150 F

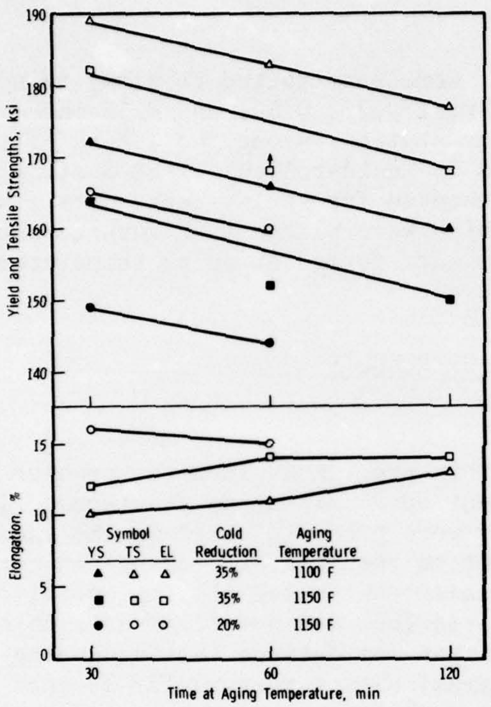


Figure 4. Longitudinal tensile properties of solution-treated-cold-rolled and aged Ti-8823 strip.

Table 1. FATIGUE BEHAVIOR OF SOLUTION-TREATED-AND-COLD-ROLLED Ti-8823 STRIP, 0.060 INCH THICK, TESTED IN ALTERNATING TENSION, R = 0.10

Aging Time, min	Specimen Number	Alternating Stress, psi	Cycles to Failure	Remarks
a. Aged at 1100 F				
30	1	40,000	(3,643,000)*	Specimen holder broke, bending specimen.
	2	50,000	28,000	Break in outer third gage length (GL), central origin.
	3	45,000	(51,200)	Break outside GL in radius.
	4	40,000	(34,400)	Break outside GL in radius.
	5	40,000	10,124,300	No break, specimen removed.
	6	42,500	28,900	Break in outer third GL, edge origin.
60	1	40,000	(77,200)	Break outside GL in radius.
	2	40,000	40,500	Break in outer third GL, edge origin.
	3	30,000	(6,585,300)	Broken in bending by surge of testing machine.
	4	35,000	10,210,000	No break, specimen removed.
	5	40,000	364,500	Break in outer third GL, central origin.
	6	37,500	10,435,000	No break, specimen removed.
120	1	40,000	(40,500)	Break outside GL in radius.
	2	40,000	(67,400)	Break outside GL in radius.
	3	40,000	(6,553,200)	Broken in bending by surge of testing machine.
	4	50,000	500,100	Break in middle third GL, central origin.
	5	45,000	26,900	Break in middle third GL, central origin.
	6	45,000	40,200	Break in outer third GL, central origin.
b. Aged at 1150 F				
30	1	40,000	10,583,200	Break in outer third GL, central origin.
	2	50,000	24,100	Break in outer third GL, central origin.
	3	45,000	(1,874,400)	Broken in bending by surge of testing machine.
	4	45,000	54,500	Break in outer third GL, central origin.
	5	45,000	19,800	Break in outer third GL, central origin.
	6	42,500	(6,504,300)	Break in outside GL in radius.
60	1	40,000	2,063,500	Break in outer third GL, edge origin.
	2	50,000	15,000	Break in outer third GL, edge origin.
	3	45,000	2,800	Break in middle third GL, central origin.
	4	37,500	1,445,900	Break in outer third GL, edge origin.
	5	42,500	67,600	Break in middle third GL, edge origin.
	6	35,000	10,000,000	No break, specimen removed.

*Parenthetical values are questionable, see "Remarks".

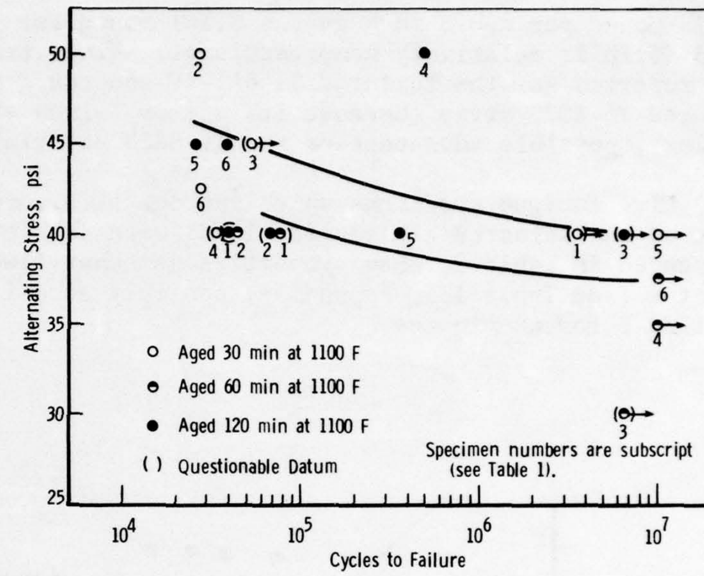


Figure 5a. Fatigue behavior of solution-treated-and-cold-rolled Ti-8823 strip, 0.06 inch thick, tested in alternating tension, R = 0.10, after aging at 1100 F.

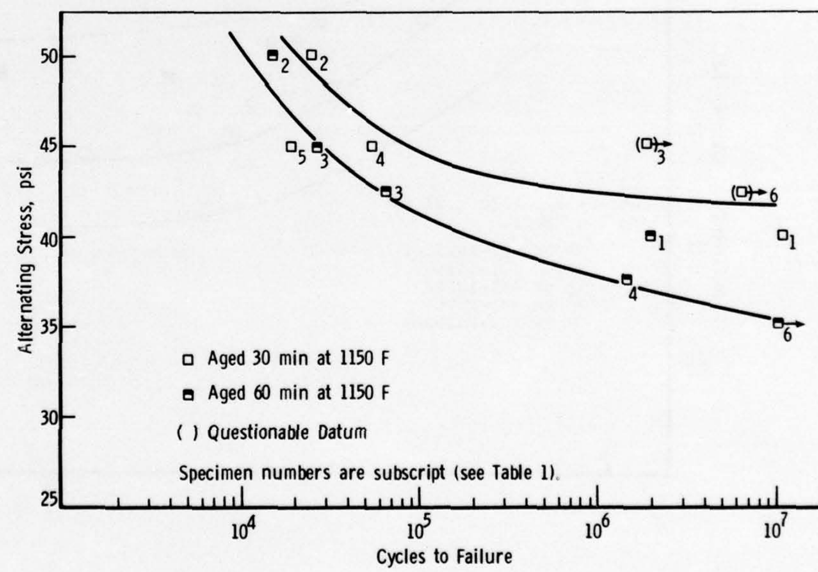


Figure 5b. Fatigue behavior of solution-treated-and-cold-rolled Ti-8823 strip, 0.06 inch thick, tested in alternating tension, R = 0.10, after aging at 1150 F.

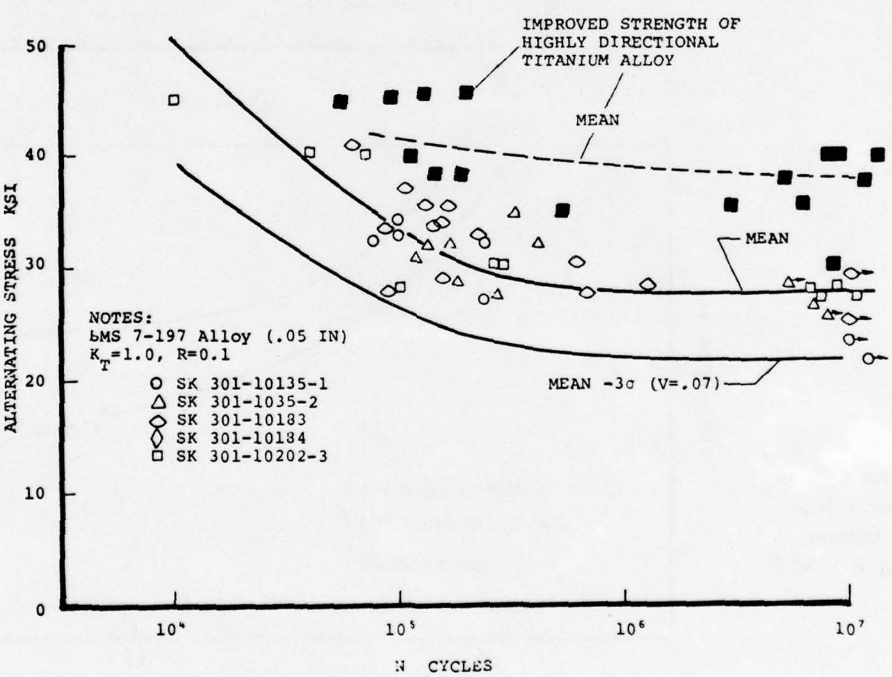
performed better than those aged 60 minutes at this temperature. A run-out stress of 42.5 ksi is projected for 30 minutes aging treatment at 1150 F.

Some difficulties were experienced with control of the fatigue testing machine which in several instances promoted premature failure in compression (see data marked "questionable"). Other questionable data represent failures initiating in the radii of the specimens.

Although these projected run-out values are considerably higher than the mean for standard Ti-6Al-4V annealed strip, they are not substantially better than those of highly directional (textured) strip of that same alloy (see Boeing data, Figure 6). It is well to note, moreover, that Ti-8823 has a density of

0.175 pound per cubic inch versus 0.161 pound for Ti-6Al-4V. However, the Ti-8823 strip is relatively nondirectional. Since transverse fatigue properties are not reported for the textured Ti-6Al-4V and could not be obtained from the cold-reduced Ti-8823 strip (because its narrow 6-inch width precluded specimen preparation), possible advantage of the Ti-8823 material is a matter of conjecture.

Five fatigue specimens which ran out (i.e., remained unbroken after 10^7 cycles at the selected alternating load) were submitted for tension test. The data, presented in Table 2, show properties somewhat lower than reported by the contractor (see Table III, Appendix), possibly excepting the single specimen aged at 1150 F for 60 minutes.



THE BOEING COMPANY
PREPARED BY: S. Beshore
CHECKED BY: R. Sandford
DATE: 9-28-73
NUMBER D210-10704-1
REV LTR A
MODEL NO.

Figure 6. S-N data for 6Al-4V titanium alloy.

Table 2. RESIDUAL TENSILE PROPERTIES OF SOLUTION-TREATED, COLD-ROLLED, AND AGED Ti-8823 STRIP, 0.060 INCH THICK, PREVIOUSLY TESTED* TO RUN-OUT IN ALTERNATING TENSION, R = 0.10

Aging Temp (deg F)	Aging Time (min)	Specimen No.	Yield Strength (ksi) 0.2% Offset	Tensile Strength (ksi)	Elon. (%)	Elastic Modulus (psi)
1100	30	1	161.4	172.8	12.0	16.1 × 10
1100	30	5	161.4	173.5	12.5	16.5
1100	60	4	155.2	169.8	10.0	15.2
1100	60	6	162.2	174.3	10.0	16.1
1150	60	6	154.9	165.6	15.0	15.4

*See Table 1.

Creep Forming

Experiments were undertaken with the hope that conformity with the 0.25-inch-radius pin could be obtained by creep forming during the aging cycle. This did not prove possible, although symmetrical loading of 15 pounds per inch per side (i.e., 15 pounds on each end of a 1-inch-wide specimen) was sufficient to achieve the 0.75-inch radius in 120 minutes at 1100 F (see Figure 2). Most of the deformation occurred within a few minutes, but then aging set in and relatively less change took place with increasing time. Increase of edge loading beyond the 15 lb/inch/side value was deemed unattractive, because of space limitation and problems of attachment in the actual nose cap forming operation.

Die Forming

It had been hoped by creep forming during aging to avoid a high temperature cycle such as that necessary to creep form Ti-6Al-4V strip to nose cap contours. Since high temperature creep forming of titanium alloys leads to costly removal of oxygen-contaminated surface metal and would likely give rise to quality control problems in production, experimental die forming of Ti-8823 strip to simulated nose cap contours was undertaken to explore this possibility as an alternative low temperature forming process.

Attempts to cold form 0.75-, 0.50-, and 0.25-inch nose radii from 1-inch-wide samples of the strip revealed that the 0.75- and 0.50-inch radii could be achieved, but considerable spring-back occurred on removal from the dies. The samples broke before cold conformity with the 0.25-inch radius was obtained.

When cold formed and then aged in the dies (by placing the die assemblies in an electric furnace), samples displayed no spring-back upon removal. Similarly, when samples were placed between dies already at aging temperature (1100 F) all three nose radii were easily achieved and no spring-back occurred after aging and removal from the die assembly. It would appear, therefore, that warm die forming could be employed to fashion the nose cap section. However, construction of equipment for such an operation would be very costly and present a number of technical problems.

RECOMMENDATIONS

Whereas the HLH nose cap presents unusual forming and fabrication difficulties because of its length, shorter nose caps (for other helicopters) and various airframe structures should be considered for advantages to be realized through application of warm-die-formed Ti-8823 sheet and strip. Results of this investigation suggest that parts could be formed and aged in warm dies using cycles possibly as brief as five minutes. By proper choice of aging temperature, a wide range of useful properties may be obtained, including, as demonstrated, high specific fatigue strength.

Another factor worthy of investigation is material cost. Ti-8823 strip, solution treated and cold reduced for rapid aging response, is readily producible by continuous rolling and continuous vacuum-heat-treatment operations. Accordingly, it may prove to be a less expensive mill product than strip or sheet of other titanium alloys.

CONCLUSIONS

1. Cold rolling has been shown to accelerate aging response of solution-treated Ti-8Mo-8V-2Fe-3Al alloy (Ti-8823) strip. Several combinations of cold reduction and aging appear useful for obtaining reproducibly a wide range of mechanical properties with limited directionality.

2. Strip of Ti-8823 solution-treated and cold-rolled 35% to 0.060 inch in thickness displayed a run-out value of 42.5 ksi when tested in tension-tension fatigue (R = 0.10) after aging 30 minutes at 1150 F. Comparable values were determined for similar strip aged 30 and 120 minutes at 1100 F.

3. On the basis of these results, solution treated/35% cold rolled/aged Ti-8823 strip 0.060 inch thick satisfies fatigue strength requirements for the nose cap of the main rotor blade of the developmental heavy lift helicopter HLH.

4. Creep forming the nose cap section from solution-treated/35% cold-rolled Ti-8823 strip during the aging cycle is not possible with edge loads equivalent to those used in production of prototype nose caps under the HLH-ATC program. Since recourse to higher edge loads is considered undesirable, the alloy does not appear to be a suitable alternate material if this creep forming practice were to be used in quantity production of HLH.

5. Warm die forming the nose cap section from solution-treated/35% cold-rolled Ti-8823 strip is possible, but could require equipment development. Warm-die-formed sections would offer the advantages of minimal spring-back and negligible surface contamination.

APPENDIX.

Item A002

FINAL REPORT
on

EFFECT OF COLD REDUCTION ON THE AGING RESPONSE

OF Ti-8Mo-8V-2Fe-3Al ALLOY STRIP

Contract No. DAAG46-74-C-0030

to

Army Materials and Mechanics Research Center
Watertown, Massachusetts

from

G. A. Lenning
TIMET
Toronto, Ohio

July 2, 1974

OBJECT

To determine the effect of cold rolling reduction on the aging response of Ti-8Mo-8V-2Fe-3Al alloy strip.

SUMMARY

Considerable promise for the approach of cold rolling to accelerate aging response of the Ti-8Mo-8V-2Fe-3Al alloy was demonstrated. Several combinations of cold reduction and aging appear useful and reproducible for developing a wide range of strengths. In the range of 145 to 180 Ksi yield strength it would appear possible to develop reproducible properties within what is known of the range of current control on forming and sizing variables. As strength level aim increases control of the variables would become more critical. Additional study of the effect of heat-to-heat, penultimate reduction-anneal cycles and aging variables would be required before control limits on strength could be established.

An unexpected range of instability was found in the cold reduction-aging temperature-aging time range examined where reproducibility is questionable even with laboratory control of aging temperature. The data obtained, however, indicate that process variables could be chosen to avoid this unstable range.

INTRODUCTION

The Ti-8Mo-8V-2Fe-3Al alloy is an age hardenable beta titanium alloy readily produced as a unidirectionally rolled strip material. Normally, beta alloy materials are supplied in the cold rolled plus solution annealed 1450F, 788C condition. The fabricator hot or cold forms the desired shape and then ages the formed part at 1000 to 1100F, 538 to 593C for times up to 16 hours in dies to retain the formed shape. Cold work following the solution anneal is known to accelerate the aging reaction in most age hardenable alloys, and preliminary data indicate this acceleration of aging exists in the Ti-8Mo-8V-2Fe-3Al alloy.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP –
Stuart V. Arnold and Paul J. Doyle

Technical Report AMMRC TR 76-41, December 1976,
19 pp, illus-tables, AMCMS Code 692000.75014

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Heat treatment
Mechanical properties

Continuous strip of Ti-8Mo-8V-2Fe-3Al was investigated for possible application in the nose cap for the main rotor blade of the Heavy Lift Helicopter as part of the Advanced Technology Component Program. Aging response of strip solutionized in a continuous vacuum annealing furnace and subsequently cold rolled was determined as functions of time and temperature for several levels of cold reduction. Tensile and fatigue properties of strip produced by selected practices were measured. Feasibility of creep forming solutionized-and-cold-rolled strip to nose cap contours during aging was explored. Warm die forming and aging of strip to those same contours was demonstrated.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP –
Stuart V. Arnold and Paul J. Doyle

Technical Report AMMRC TR 76-41, December 1976,
19 pp, illus-tables, AMCMS Code 692000.75014

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Heat treatment
Mechanical properties

Continuous strip of Ti-8Mo-8V-2Fe-3Al was investigated for possible application in the nose cap for the main rotor blade of the Heavy Lift Helicopter as part of the Advanced Technology Component Program. Aging response of strip solutionized in a continuous vacuum annealing furnace and subsequently cold rolled was determined as functions of time and temperature for several levels of cold reduction. Tensile and fatigue properties of strip produced by selected practices were measured. Feasibility of creep forming solutionized-and-cold-rolled strip to nose cap contours during aging was explored. Warm die forming and aging of strip to those same contours was demonstrated.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP –
Stuart V. Arnold and Paul J. Doyle

Technical Report AMMRC TR 76-41, December 1976,
19 pp, illus-tables, AMCMS Code 692000.75014

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Heat treatment
Mechanical properties

Continuous strip of Ti-8Mo-8V-2Fe-3Al was investigated for possible application in the nose cap for the main rotor blade of the Heavy Lift Helicopter as part of the Advanced Technology Component Program. Aging response of strip solutionized in a continuous vacuum annealing furnace and subsequently cold rolled was determined as functions of time and temperature for several levels of cold reduction. Tensile and fatigue properties of strip produced by selected practices were measured. Feasibility of creep forming solutionized-and-cold-rolled strip to nose cap contours during aging was explored. Warm die forming and aging of strip to those same contours was demonstrated.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
WARM-DIE-FORMING OF BETA TITANIUM ALLOY STRIP –
Stuart V. Arnold and Paul J. Doyle

Technical Report AMMRC TR 76-41, December 1976,
19 pp, illus-tables, AMCMS Code 692000.75014

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Heat treatment
Mechanical properties

Continuous strip of Ti-8Mo-8V-2Fe-3Al was investigated for possible application in the nose cap for the main rotor blade of the Heavy Lift Helicopter as part of the Advanced Technology Component Program. Aging response of strip solutionized in a continuous vacuum annealing furnace and subsequently cold rolled was determined as functions of time and temperature for several levels of cold reduction. Tensile and fatigue properties of strip produced by selected practices were measured. Feasibility of creep forming solutionized-and-cold-rolled strip to nose cap contours during aging was explored. Warm die forming and aging of strip to those same contours was demonstrated.

The purpose of this investigation was to determine if the aging characteristics of cold reduced material can be controlled sufficiently for practical application. The advantages of accelerated aging would be lowered costs by decreasing age time and the expense of contamination removal. The three prior reports covered preparation and hardness test results.

MATERIALS AND PROCEDURES

The starting material for this investigation was approximately 0.150-in. gage x 36-in. wide hot band rolled at 2050F. The ingot number was K5055 which analyzed:

Element	Wt,%
Mo	8.0
V	8.2
Fe	2.0
Al	3.0
O_2	0.14
N_2	0.011

The material from this particular coil had been rolled to strip and thoroughly evaluated at 0.060, 0.040, and 0.020-in. gage for an internal development program at TIMET.

The material for the present investigation was rolled as short panels without tension applied on a 2-high, 4-high Fenn laboratory mill. This mill is normally used for research and development studies on new alloys and processes before application to the production Zendzimir mill in the Toronto Plant.

The electrical resistance laboratory furnace used for the solution anneal treatments of 1450F-8mins has a cycle of ±7F around the control point which is less than the cycle for production type furnaces. This same furnace was used for aging where the thermal cycle in the 1100 to 1250F range was plus or minus 15F, but again less than for conventional production furnaces used for aging. Furnace temperatures were measured with chromel-alumel thermocouples and a semi-precision potentiometer. Aging times are time at temperature as measured with the thermocouple resting on top of the pieces being aged. All aging was by placing the cold material in a hot furnace so as to minimize heat-up time.

Levels of cold reduction investigated were 35, 50, and 58 per cent with aging at 1100, 1150, 1200, and 1250F for times of 5, 30, 60, 120, 240, 480, and 960 minutes. An additional reduction level of 20% was also examined for 1150F aging for the times above. Penultimate reduction was varied to give a 0.060-in. gage final at all reduction levels.

Hardness was determined on a section through the 0.060-in. sheet thickness using the elongated indenter with the long axis parallel to the sheet surface. The five hardness impressions were all placed in a line at the mid thickness level through the sheet. The hardness tester was calibrated prior to use on this program by a factory representative, and the single operator who took the readings checked the machine with a calibrated test block immediately prior to starting the program. The tensile machine used is a screw driven Riehle having multiple load ranges up to 120,000 pounds.

RESULTS

Knoop hardness results are shown in Table I. The accelerating effect of cold reduction on aging kinetics is readily apparent from comparison of these data with those in reference 1. For example, the 35% cold reduced material aged to a peak hardness at 1100F sometime between 5 minutes and 60 minutes; whereas, the as-solution annealed material in reference 1 had hardness increasing out to 24 hours. At 50 and 58% cold reduction, maximum hardness at 1100F was reached in less than 30 minutes and possibly less than 5 minutes.

The secondary aging peak at 240 minutes shown for the 35% cold reduced aged at 1150F for 120 minutes and longer condition also occurred for other conditions, e.g. 58% cold reduced and aged at 1150F for 60 minutes. This secondary hardening remains an anomaly outside the scope of the present study. Metallographic examination showed some evidence of recrystallization in samples aged longer than 120 minutes at 1250F for the 58% cold reduced material. The trend toward a secondary peak was reproducible as shown in Table II for this same 35% cold reduced material aged at 1150F and for re-rolled and re-aged material. The hardness level of 333 for the re-rolled and re-aged was somewhat lower than the 357 and 356 values obtained for the original material indicating an unstable region which should probably be avoided in view of the aims of the present program.

Other areas of the aging temperature-time relations, such as 50% cold reduced and aged at 1100, 1200, and 1250F appeared reasonably reproducible as shown by comparison of Table I and Table II results.

Tensile results for selected conditions are shown in Table III. These values are consistent among themselves; and when yield and tensile strengths are compared against hardness, a reasonable correlation is obtained with all points on a graph of strength vs. hardness in a ±6 Ksi band. Reproducibility was also good for the 1100F-120minute aging of the 35% cold reduced material (see footnote).

RECOMMENDATIONS FOR FUTURE WORK

Obviously, process capabilities and other factors unknown at this time will weigh heavily on future plans. From the standpoint of the roller, factors needed to establish a process for making cold rolled material to a specific gage would be 1) importance of controlling reduction level, and 2) the effect of reduction and annealing practice from hot band gage, 0.15 to 0.18-in., to the gage for annealing. Fabrication of the finished part is more complicated; but the factors of aging temperature control, aging time, and rate of heating to the age temperature should be considered and investigated relative to process capabilities.

TABLE I

Aging Response of Ti-8Mo-8V-2Fe-3Al Alloy Strip for Three Levels of Cold Reduction as Determined by Hardness

Aging Treatment		Knoop Hardness 1.0Kg[1]			
Temp,F	Time, Mins.	20% Cold Rolled & Aged	35% Cold Rolled & Aged	50% Cold Rolled & Aged	58% Cold Rolled & Aged
0	0	329	311	314.8	326.7
1100	5		372.3	391.7	388
	30		383.6	373.1	373.8
	60		376.5	368.5	367.8
	120		367	356.8	363.3
	240		357.5	355.7	357.1
	480		354.3	354.3	353.3
	960		345.6	348	346
1150	5	336	345.6	350.8	359.7
	30	334	348.7	357.5	348.4
	60	335	347	344.3	388.8
	120	319	337.9	333.7	370.4
	240	319	357.1	336.6	345.6
	480	316	341.6	331.1	346.7
	960	303	334	328.9	340.6
1200	5		340.6	331.1	327.9
	30		338.9	321.8	318.7
	60		327.9	318.4	313.0
	120		325.7	322.4	304.2
	240		317.8	313.0	298.9
	480		325.4	308.4	317.5
	960		313.3	308.7	321.8
1250	5		316.9	303	323
	30		319	306.7	314.2
	60		311.6	299.7	318.4
	120		309.8	299.7	310.7
	240		309.5	300.2	312.2
	480		298.3	297.5	307.2
	960		299.7	301.4	301.6

[1]Values shown are the average of five readings.

TABLE II

Retests for Aging Response of Ti-8Mo-8V-2Fe-3Al Alloy Strip for Levels of Cold Reduction Indicated

Aging Treatment		Knoop Hardness 1.0 Kg		
Temp,F	Time,Mins.	35% Cold Rolled and Aged	50% Cold Rolled and Aged	58% Cold Rolled and Aged
1100	5	-	382	-
	30	-	367	-
	120	-	363	-
	480	-	353	-
1150	30	-	-	333.4
	60	-	-	335
	120	348*, 329.9	-	-
	240	356*, 333.1	-	-
1200	5	-	342	-
	30	-	329	-
	120	-	327	-
	480	-	320	-
1250	5	-	314	-
	30	-	311	-
	120	-	312	-

*These values are for same pieces prepared for original results. Unmarked values are for newly rolled and aged materials.

TABLE III

Aging Response of
Cold Rolled Ti-8Mo-8V-2Fe-3Al Alloy Strip
as Determined by Tensile Properties

Cold Reduction, %	Aging Temp, F	Aging Time, Mins.	Test Direction	Tensile Properties UTS, Ksi	YS, Ksi	Elong, %
20	1150	30	L	165	149	16
"	"	"	T	169	157	12
"	"	60	L	160	144	15
"	"	"	T	169	150	12
35	no	-	L	161	145	12
"	no	-	T	165	137	10
"	1100	30	L	189	172	10
"	"	"	T	198	187	7
"	"	60	L	183	165	11
"	"	"	T	194	180	9
"	"	120	L	177	160	13
"	"	"	T	187	174	8
35[1]	1100	120	L	178	162	13
"[1]	"	"	T	186	174	7
"[1]	"	480	L	171	154	11
"[1]	"	"	"	171	154	12
"	"	"	T	179	165	9
"	"	"	"	179	167	10
35	1150	30	L	182	164	12
"	"	"	T	190	178	8
"	"	60	L	168	152	14
"	"	"	T	173	162	10
"	"	120	L	168	150	14
"	"	120	T	178	165	10

[1]Samples rolled and aged independently of prior samples.

REFERENCES

1) Hunter, D. B., "Metastable Beta Sheet Alloy Ti-8Mo-8V-2Fe-3Al," Final Technical Report, Part 1, WAL TR 405/2-14 on Contract DA-30-069-ORD-3743, October, 1966.

a. Longitudinal

b. Transverse

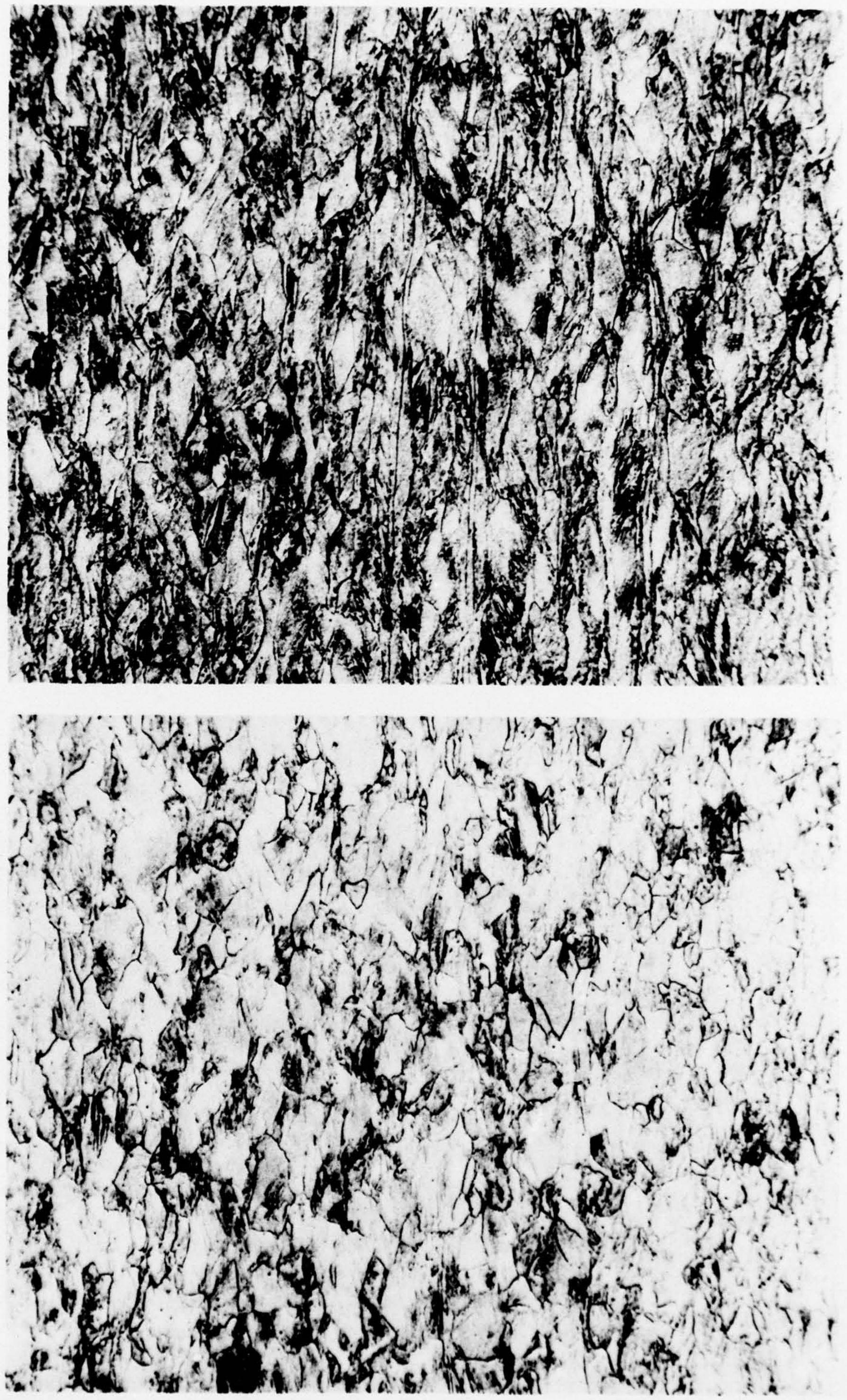


Figure A-1. Microstructures of Ti-8823 strip solution-treated, cold-rolled 35%, and aged 1150 F for 30 minutes. Mag. 100X

DISTRIBUTION LIST

No. of Copies	To
	Director of Defense Research and Engineering, Dept. of Defense, Pentagon, Washington, D. C. 20301
1	ATTN: OSD-ODDR&E, Deputy for Aeronautics/E.T.
	Office of the Assistant Secretary of Defense (I&L), The Pentagon (Rm 2B329), Washington, D. C. 20301
1	ATTN: Mr. Alexander Tedesco
1	Headquarters, Department of the Army (DALO-AV), Washington, D. C. 20310
12	Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314
1	Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201
	Commander, U. S. Army CINCPAC Support Group, APO San Francisco 96558
1	ATTN: MOCG-LO
	Headquarters, Department of the Army (DAMA-WSA), Room 3B454, Pentagon, Washington, D. C. 20310
1	ATTN: Mr. Richard L. Ballard
	Commander, U. S. Army Materiel Development and Readiness Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333
1	ATTN: DRCDE-DH
1	DRCLDC, Mr. R. Zentner
	Chief of Research and Development, Department of the Army, Washington, D. C. 20310
2	ATTN: Physical and Engineering Sciences Division
	Commander, Army Research Office, P. O. Box 12211, Research Triangle Park, North Carolina 27709
1	ATTN: Information Processing Office
1	Engineering Science Division
	Commander, U. S. Army Aviation Systems Command, P. O. Box 209, Main Office, St. Louis, Missouri 63166
2	ATTN: DRSAV-ZDR
	Director, U. S. Army Air Mobility Research and Development Laboratory, P. O. Box 209, Main Office, St. Louis, Missouri 63166
1	ATTN: SAVDL-SR
2	Director, U. S. Army Air Mobility Research and Development Laboratory, Ames Research Center, Moffett Field, California 94035
1	Ames Directorate, U. S. Army Air Mobility Research and Development Laboratory, Ames Research Center, MS-215-1, Moffett Field, California 94035
2	Langley Directorate, U. S. Army Air Mobility Research and Development Laboratory, MS-266, NASA-Langley Research Center, Hampton, Virginia 23665
2	Lewis Directorate, U. S. Army Air Mobility Research and Development Laboratory, MS-77-5, NASA-Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135
	Commander, U. S. Army Aviation Engineering Flight Activity, Edwards AFB, California 93523
2	ATTN: SAVTE-A, Reference & Research Library
1	Commander, U. S. Army Scientific and Technical Information Team (Europe), Box 48, APO New York 09710
	U. S. Army Aeromedical Research Laboratory, P. O. Box 577, Fort Rucker, Alabama 36360
1	ATTN: Commander
1	Scientific Advisor
1	Commander, U. S. Army Mobility R&D Center, Petroleum and Materials Department, Fuels, Lubricants and Coatings Division, Fort Belvoir, Virginia 22060

No. of Copies	To
1	Director, Human Engineering Laboratories, Aberdeen Proving Ground, Maryland 21005
1	ATTN: Technical Reports Office
	Commander, U. S. Army Natick Research and Development Command, Natick, Massachusetts 01760
1	ATTN: DRXNM-CCE
1	DRXNM-PRBN (Psychology Laboratories)
1	Technical Library
	Director, U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland 21005
1	ATTN: DRXBR-BL
	Director, U. S. Army Fuels and Lubricants Laboratory, Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas 78228
1	ATTN: Mr. J. T. Gray
1	Director, Plastics Technical Evaluation Center, Picatinny Arsenal, Bldg. 3401, Dover, New Jersey 07801
1	ATTN: SARPA-FR-M-D, PLASTEC, A. M. Anzalone
	Commander, U. S. Army Test and Evaluation Command, Aberdeen Proving Ground, Maryland 21005
1	ATTN: DRSTE-BG
	Director, U. S. Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, Maryland 21005
1	ATTN: AMXSY-CM (Mr. Reiher)
	Commander, U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703
1	ATTN: DRSEL-GG-DD
1	DRSEL-GG-DM
1	DRSEL-CT-A
1	DRSEL-WL-N (Mr. Max Adler)
	Commander, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
1	ATTN: Technical Library
1	DRSMI-RB
1	DRSMI-RSM, Mr. E. J. Wheelahan
	Commander, U. S. Army Armament Command, Rock Island, Illinois 61201
2	ATTN: Technical Library
	Commander, Frankford Arsenal, Philadelphia, Pennsylvania 19137
1	ATTN: Library, H1300, Bl. 51-2
1	SARFA-L300, Mr. J. Corrie
	Commander, U. S. Army Foreign Science and Technology Center, 220 7th Street, N. E., Charlottesville, Virginia 22901
1	ATTN: DRXST-SD2
	Commander, U. S. Army Tank-Automotive Research and Development Command, Warren, Michigan 48090
2	ATTN: DRDTA, Research Library Branch
	Deputy Commandant for Combat & Training Developments, U. S. Army Aviation School, Fort Rucker, Alabama 36360
1	ATTN: ATST-CTD-D2
1	ATST-CTD-D4
	Commandant, U. S. Army Transportation School, Fort Eustis, Virginia 23604
1	ATTN: ATSP-CTD
1	Marine Corps Liaison Officer
	Commander, U. S. Army Medical R&D Command, Washington, D. C. 20314
1	ATTN: MEDDH-SI
	Commander, DA Edgewood Arsenal, Edgewood Arsenal, Maryland 21010
1	ATTN: SAREA-RA, Mr. A. Flatau, Chief, Aerodynamic Research Group

No. of Copies	To
	Commandant, U. S. Army Command and General Staff College, Fort Leavenworth, Kansas 66027
1	ATTN: Acquisitions, Library Division
	President, U. S. Army Aviation Test Board, Fort Rucker, Alabama 36360
2	ATTN: STEBG-MO
	U. S. Army Arctic Test Center, Test Engineering Branch, APO Seattle, Washington 98733
1	ATTN: Aviation Test Section
	Commander, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama 36362
1	ATTN: Librarian, Bldg. 4905
	Hq Air Force Systems Command, U. S. Army Field Office, Andrews Air Force Base, Washington, D. C. 20334
1	ATTN: AMXFA (SDOA)
1	AFFTC (DOEEP) Edwards Air Force Base, California 93523
	Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio 45433
1	ATTN: SFL/Mr. H. Jones
	Commander, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio 45433
1	ATTN: FXM, Mr. Clark
1	AFFDL/FBS
1	AFFDL/FGC
1	AFFDL/FES
1	AFFDL/DOO, Technical Library, Bldg. 45
	Air Systems Division, Wright-Patterson AFB, Ohio 45433
1	ATTN: ASD/ENFDP
1	ASD/ENJET
	Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433
1	ATTN: AFML/LAE, Mr. T. Reinhart
1	AFML/LPH, G. H. Griffith
1	AFML/MXE, E. J. Morrissey
1	AFML/LPT, Mr. Robert Van Vliet
1	AFML/LLN, Dr. J. P. Henderson
1	AFML/LC
1	AFML/LLP, D. M. Forney, Jr.
1	AFML/MBC, Mr. Stanley Schulman
	4950 TESTW/TZHM, Wright-Patterson Air Force Base, Ohio 45433
1	ATTN: Mr. Johns
	Commander, Naval Air Systems Command, Department of the Navy, Washington, D. C. 20360
1	ATTN: Rotary Wing Acft Br, Code AIR 5106
1	Code AIR-503D
1	AIR 53643, Mr. S. M. Collegeman
2	Tech Library (Code AIR-604)
1	AIR-53011
1	AIR-5104
1	AIR-5304
1	AIR-5364
1	AIR-5302
1	AIR-530214
1	AIR-530112
1	AIR-53014
	Chief of Naval Research, Department of the Navy, Arlington, Virginia 22217
1	ATTN: Code 438
1	Code 461
1	Code 470
1	Code 471
	Naval Research Laboratory, Washington, D. C. 20390
1	ATTN: Code 8430, Dr. J. M. Krafft
2	Code 6382, Dr. G. R. Yoder
	Commander, Naval Safety Center, Naval Air Station, Norfolk, Virginia 23511
1	ATTN: Life Sciences Department
	Commander, Naval Air Rework Facility, Naval Air Station, Norfolk, Virginia 23511
1	ATTN: Code 350
	Commander, U. S. Naval Air Test Center, Patuxent River, Maryland 20670
1	ATTN: Flight Test Division
	Commander, Naval Air Development Center, Warminster, Pennsylvania 18974
1	ATTN: Code 503, Paul Young
1	Aero Mechanics Dept., Code AM
1	Aero Materials Dept., Code MA
1	Aero Structures Dept., Code ST-1
	Commander, U. S. Naval Weapons Laboratory, Dahlgren, Virginia 22448
1	ATTN: Code EAA, Mr. W. Mannschreck
	Commander and Director, Naval Ship Research and Development Center, Bethesda, Maryland 20084
1	ATTN: David W. Taylor, Code 522-3, Aerodynamics Library
	Commander and Director, Naval Ship Research and Development Center, Washington, D. C. 20034
1	ATTN: Code 630, Robert Williams
1	Sea-Based Aviation Dept.
1	Commandant (GDST-1/62), U. S. Coast Guard, 400 7th Street, S.W., Washington, D. C. 20590
	Transportation Systems Center, Department of Transportation, 55 Broadway, Cambridge, Massachusetts 02142
1	ATTN: Dr. George Kovatch, Code TM
	NASA Headquarters, Aeronautical Vehicles Division, Washington, D. C. 20546
1	ATTN: Code RAO, Mr. John H. Enders
	National Aeronautics and Space Administration, Washington, D. C. 20546
1	ATTN: Mr. B. G. Achhammer
1	Mr. G. C. Deutsch - Code RR-1
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama 35812
1	ATTN: R-P&VE-M, R. J. Schwinghamer
1	S&E-ME-MM, Mr. W. A. Wilson, Building 4720
	National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California 94035
1	ATTN: Mr. Dave Hickey
1	John McCloud III, Mail Stop 221-2, Large Scale Aerodynamics Branch
1	Technical Library
	National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia 23665
1	ATTN: Mr. Robert J. Tapscott, Flight Research Branch, LSAD, M/S 249
1	Technical Library, Langley Field
	Director, National Aeronautics and Space Administration, Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135
1	ATTN: Chief, Library
	Director, National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas 77058
1	ATTN: Code BM6
	Federal Aviation Administration, Great Lakes Region, 2300 E. Devon, Des Plaines, Illinois 60018
1	ATTN: Marvin J. Walker, MS-AGL-214

No. of Copies	To
1	Department of Transportation Library, FOB-10A Services Branch, TAD-494.6, 800 Independence Avenue, S.W., Washington, D. C. 20590
	Federal Aviation Administration, Federal Building, J. F. Kennedy International Airport, Jamaica, N. Y. 11430
1	ATTN: Eastern Region Library, EA-49
	Federal Aviation Administration, 800 Independence Avenue, S.W., Washington, D. C. 20590
1	ATTN: Systems Research & Development Service, RD-742
1	Engineering & Manufacturing Division, FS-120
	Federal Aviation Administration, 2100 Second Street, S.W., Washington, D. C. 20591
1	ATTN: Chief, Aircraft Safety & Noise Abatement Division, ARD-500, Systems Research & Development Service
1	LTC Thomas C. West, ARD-531 SRDS
	Federal Aviation Administration, Civil Aeromedical Institute, P. O. Box 25082, Oklahoma City, Oklahoma 73125
1	ATTN: CAMI Library, AC-922
1	Chief, Safety Analysis and Promotion Division, Bureau of Aviation Safety, NA87A, National Transportation Safety Board, Washington, D. C. 20591
	U. S. Government Printing Office, Division of Public Documents, Washington, D. C. 20402
1	ATTN: Library
1	Aerophysics Company, 3500 Connecticut Avenue, N.W., Washington, D. C. 20008
1	Airesearch Manufacturing Company, A Division of the Garrett Corporation, 402 South 36th Street, Phoenix, Arizona 85034
1	Air Vehicle Corporation, 8873 Balboa Avenue, San Diego, California 92123
	General Motors Corporation, Detroit Diesel Allison Division, Indianapolis, Indiana 46206
1	ATTN: Mr. N. E. Eggers, Mgr., Aerospace Sales, Dept. 7827, Mail Stop U-9
	American Power Jet Company, 705 Grand Avenue, Ridgefield, New Jersey 07657
1	ATTN: G. Chernowitz, Director
	Arizona State University, Tempe, Arizona 85281
1	ATTN: Dr. James Turnbow
1	Crash Survival Investigators School, College of Engineering Sciences
	Aurburn University, Auburn, Alabama 36830
1	ATTN: Aerospace Engineering Department
	Autonetics, Division of North American Rockwell Corporation, 3370 Miraloma Avenue, P. O. Box 4171, Anaheim, California 92806
1	ATTN: Mr. H. L. Ehlers, D/344-17, BD18
	AVCO Corporation, Lycoming Division, 550 Main Street, Stratford, Connecticut 06497
1	ATTN: Technical Library
	Beech Aircraft Corporation, 9709 East Central, Wichita, Kansas 67206
1	ATTN: Aerospace Marketing & Contracts
	Bell Aerosystems Company, P. O. Box 1, Buffalo, New York 14240
1	ATTN: Technical Library, C-87
	Bell Helicopter Company, Division of Textron, P. O. Box 482, Fort Worth, Texas 76101
1	ATTN: Engineering Library
1	Chief, Research Administration

No. of Copies	To
	The Boeing Vertol Company, P. O. Box 16858, Philadelphia, Pennsylvania 19142
1	ATTN: Mr. W. C. Boehm (P32-23)
1	Technical Librarian (P32-01)
	Bolt, Beranek, and Newman, Inc., Cambridge, Massachusetts 02138
1	ATTN: Shelden Baron
1	Booz-Allen Applied Research, Inc., 4733 Bethesda Avenue, Bethesda, Maryland 20014
	California Institute of Technology, Guggenheim Aeronautical Laboratory, Pasadena, California 91109
1	ATTN: Aeronautics Library
1	Cessna Aircraft Company, Box 1877, Wichita, Kansas 67201
	Conrac Corporation, New Jersey Division, 32 Fairfield Place, West Caldwell, New Jersey 07006
1	ATTN: Mr. Max Umles, Project Manager
1	Teledyne CAE, 1330 Laskey Road, Toledo, Ohio 43601
	General Dynamics, Convair Division, P. O. Box 80986, San Diego, California 92138
1	ATTN: Research Library
	General Dynamics, Convair Division, P. O. Box 80847, San Diego, California 92138
1	ATTN: V. A. Chase, Mail Zone 640-04
	Calspan, P. O. Box 235, Buffalo, New York 14217
1	ATTN: Library
	Cornell University, Ithaca, New York 14850
1	ATTN: Prof. W. R. Sears, Grumman Hall
	Curtiss-Wright Corporation, Caldwell, New Jersey 07006
1	ATTN: Library
1	Del Mar Engineering Laboratories, 6901 W. Imperial Highway, Los Angeles, California 90045
	Enstrom Helicopter Corporation, Box 277, Menominee, Michigan 49858
1	ATTN: D. E. Brandt, Vice Pres. Engineering
	Fairchild Industries, Inc., Helicopter Development Center, Farmingdale, Long Island, New York 11735
1	ATTN: Mr. Frank Roberts
	Fairchild Industries, Inc., Fairchild Republic Division, Farmingdale, New York 11735
1	ATTN: Engineering Library
	Forge Aerospace, Inc., 1705 Desales Street, N.W., Washington, D. C. 20036
1	ATTN: Mr. Robert L. Kaplan
	General Dynamics Corporation, 1120 West Mercury Boulevard, Suite 210, Virginia National Bank Building, Hampton, Virginia 23366
1	ATTN: Mr. H. B. Henderson, Manager
	General Dynamics/Fort Worth, P. O. Box 748, Fort Worth, Texas 76101
1	ATTN: Research Library, 2246
1	General Electric Company, AEG Technical Information Center, N-32, Bldg. 700, Cincinnati, Ohio 45215
	General Electric Company, 718 B. J. Clyde Morris Blvd., Newport News, Virginia 23601
2	ATTN: Mr. A. A. West
	Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, Georgia 30332
1	ATTN: Dr. Arnold L. Ducoffe, Director

No. of Copies	To
1	Goodyear Aerospace Corporation, 1210 Massillon Road, Akron, Ohio 44306
1	Grumman Aerospace Corporation, Technical Information Center, Pl. 35, Dept. 313, Bethpage, New York 11714
1	Gyrodyne Company of America, Inc., St. James, New York 11780
	United Technologies Corporation, Hamilton Standard Division, Windsor Locks, Connecticut 06096
1	ATTN: Advanced Systems
1	Library
	Hayes International Corporation, P. O. Box 2287, Birmingham, Alabama 35201
1	ATTN: Engineering Library
1	Helio Aircraft Corporation, Hanscom Field, Civilian Terminal Area, Bedford, Massachusetts 01730
1	Henry V. Borst & Associates, 203 W. Lancaster Avenue, Wayne, Pennsylvania 19087
	Hughes Helicopters, Division of the Summa Corporation, Culver City, California 90230
1	ATTN: K. B. Amer, Bldg. 2, M/S T7B
1	Library
1	Mr. Robert A. Wagner, Director, Aero Engr. Div.
1	Dr. E. Robert Wood, Asst. to Technical Dept., MS-2T7B
	Illinois Institute of Technology, Chicago, Illinois 60616
1	ATTN: Prof. Irving Michelson, Technology Center
1	Kaman Aircraft, Division of Kaman Corporation, Old Windsor Road, Bloomfield, Connecticut 06002
1	ATTN: Mr. Donald W. Robinson, Jr., Chief Research & Dev. Engr.
1	F. Morrison, Librarian
1	Kellett Aircraft Corporation, Box 35, Willow Grove, Pennsylvania 19090
	Lockheed-California Company, P. O. Box 551, Burbank, California 91503
1	ATTN: Mr. A. R. Yackle, 75-23,63, Acting Division Engineer, Rotary Wing Technology
1	Central Library
	Lockheed-California Company, Department 7584, Bldg. 360, Burbank, California 91520
1	ATTN: E. R. Wood
	Lockheed-Georgia Company, Marietta, Georgia 30063
1	ATTN: Advanced Composites Information Center, Dept. 72-34 - Zone 26/RIC
1	LTV Aerospace Corporation, Vought Aeronautics Division, P. O. Box 5907, Dallas, Texas 75222
	Massachusetts Institute of Technology, Department of Aeronautics & Astronautics, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139
1	ATTN: Aeronautics & Astronautics Library, Room 33-316
2	Prof. R. Miller
	McDonnell-Douglas Aircraft Corporation, P. O. Box 516, St. Louis, Missouri 63166
1	ATTN: Helicopter Division
	McDonnell-Douglas Corporation, Doug Aircraft Division, 3855 Lakewood Blvd., Long Beach, California 90801
1	ATTN: M. Klotzsche, Manager, Adv. Systems & Res. Gov. Marketing
1	Mississippi State University, Aerophysics and Aerospace, Department of Engineering, P. O. Drawer AP, State College, Mississippi 39

No. of Copies	To
1	North American Aviation, Inc., Los Angeles Division, International Airport, Los Angeles, California 90045
1	North American Rockwell Corporation, Engineering Data Services, 4300 East Fifth Avenue, Columbus, Ohio 43216
1	Ohio State University, 2101 Robinson Lab., Columbus, Ohio 43210
1	Operations Research, Inc., 1400 Spring Street, Silver Spring, Maryland 20910
	St. Louis University, Parks College, East St. Louis, Illinois 62201
1	ATTN: B. H. Ulrich, Chairman, Aerospace Engineering
	The Pennsylvania State University, Department of Aerospace Engineering, University Park, Pennsylvania 16802
1	ATTN: Dr. Barnes W. McCormick, 233 Hammond Building
1	Engineering Librarian, 201 Hammond Building
1	Piasecki Aircraft Corporation, Island Road, International Airport, Philadelphia, Pennsylvania 19142
	Piasecki Aircraft Corporation, Island Road, International Airport, Philadelphia, Pennsylvania 19153
1	ATTN: Mr. D. N. Meyers
	Planning Research Corporation, 1100 Glendon Avenue, Los Angeles, California 90024
1	ATTN: K. L. Harms
1	Polytechnic Institute of Brooklyn, Graduate Center Library, Route 110, Farmingdale, Long Island, New York 11735
1	Pratt and Whitney Aircraft, Division of United Technologies Corporation, 400 Main Street, East Hartford, Connecticut 06108
	Princeton University, Department of Aerospace & Mechanical Sciences, James Forrestal Campus, Princeton, New Jersey 08540
1	ATTN: Library
1	Prof. Edward Seckel, Flight Research Laboratory
	RCA Government & Commercial Systems, P. O. Box 588, Burlington, Massachusetts 01803
1	ATTN: Richard J. McLaughlin, Sr. Sales Representative
1	Rensselaer Polytechnic Institute, Dept. of Aeronautical Engineering and Astronautics, Troy, New York 12181
	General Research Corporation, Operations Analysis Division, McLean, Virginia 22101
1	ATTN: Document Library/MF
	Ryan Aeronautics, San Diego, California 92112
1	ATTN: Army Manager
	Ryan Aeronautical Company, 2701 Harbor Drive, San Diego, California 92112
1	ATTN: Technical Information Services
	United Technologies Corporation, Sikorsky Aircraft Division, North Main Street, Stratford, Connecticut 06602
1	ATTN: Mr. Philip L. Michel, Chief, R&D Planning (Engr)
1	Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas 78228
	Stanford University Libraries, Stanford, California 94305
1	ATTN: Engineering Library
	Systems Control, Inc., 1801 Page Mill Road, Palo Alto, California 94304
1	ATTN: Mr. John A. Molusis
1	Technology Incorporated, 3821 Colonel Glenn Highway, Dayton, Ohio 45431

No. of Copies	To
	Texas A and M University, College of Engineering, College Station, Texas 77843
1	ATTN: A. E. Cronk, Dept. of Aero Engineering
1	Balusu M. Rao, Aerospace Engineering Dept.
	Tulane University, Dept. of Mechanical Engineering, New Orleans, Louisiana 70118
1	ATTN: Dr. K. H. Adams
1	United Technologies Corporation, Research Center, 400 Main Street, East Hartford, Connecticut 06118
	University of California, Santa Barbara, California 93106
1	ATTN: Sciences-Engineering Library
	University of Denver, Denver Research Institute, Denver, Colorado 80210
1	ATTN: Mr. William G. Howell
	University of Maryland, College Park, Maryland 20742
1	ATTN: Director, Wind Tunnel
	University of New Hampshire, Durham, New Hampshire 03824
1	ATTN: Prof. C. K. Taft, Mechanical Engineering
	University of Notre Dame, Office of Res. & Sponsored Programs, Notre Dame, Indiana 46556
1	ATTN: Dr. Francis M. Kobayashi
	University of Southern California, Institute of Aerospace Safety & Management, Admin. Bldg., Room 261, University Park, Los Angeles, California 90007
1	ATTN: Mr. Norman L. Horton
	University of California, Los Angeles, California 90024
1	ATTN: Peretz Friedmann, Asst. Prof., Mechanics and Structures Department
	University of Texas, Arlington, Texas 76010
1	ATTN: Engineering Library

No. of Copies	To
	University of Texas, Department of Aerospace Engineering, Austin, Texas 78712
1	ATTN: Engineering Library
	University of Utah, Department of Mechanical Engineering, Salt Lake City, Utah 84112
1	ATTN: Dr. L. K. Isaacson
1	University of Washington, Department of Aeronautics and Astronautics, 207 Guggenheim Hall, Seattle, Washington 98105
	Virginia Polytechnic Institute, Blacksburg, Virginia 24061
1	ATTN: Documents Dept., Carol M. Newman Library
1	Washington University, Department of Mechanical and Aerospace Engineering, St. Louis, Missouri 63130
1	Western Gear Corporation, Applied Technology Division, P. O. Box 1040, 14724 Proctor Avenue, City of Industry, California 91744
	Wichita State University, Wichita, Kansas 67208
1	ATTN: Dr. Glen W. Zumwalt, Aeronautical Engrg. Dept.
1	E. Burke Wilford, Aero & Research Engineer, Merion Station, Pennsylvania 19066
	President, General Research Corporation, McLean, Virginia 22101
1	ATTN: Library
1	Vizex, Inc., 4524 Bailey Avenue, Amherst, New York 14226
	Director, Army Materials and Mechanic Research Center, Watertown, Massachusetts 02172
2	ATTN: DRXMR-PL
1	DRXMR-AG
2	Authors

☆U.S. GOVERNMENT PRINTING OFFICE: 1977—A-0703/139